

## Improved Speed Control System for an 87,000 HP Wind Tunnel Drive

Edward A. Becks  
*NYMA, Inc.*  
*Engineering Services Division*  
*Brook Park, Ohio*

Timothy J. Bencic  
*National Aeronautics and Space Administration*  
*Lewis Research Center*  
*Cleveland, Ohio*

Philip Z. Blumenthal  
*NYMA, Inc.*  
*Engineering Services Division*  
*Brook Park, Ohio*

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**Edward A. Becks**  
Spvsr, Elect. Oper. Sect.  
NYMA, Inc.  
2001 Aerospace Parkway  
Brook Park, OH 44142

**Timothy J. Bencic**  
Electronic Oper. Eng.  
NASA Lewis Research Center  
21000 Brookpark Rd.  
Cleveland, OH 44135

**Philip Z. Blumenthal**  
Senior Engineer  
NYMA, Inc.  
2001 Aerospace Parkway  
Brook Park, OH 44142

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## **ABSTRACT**

This paper describes the design, installation, and integrated systems tests for a new drive motor speed control system which was part of a recent rehab project for the NASA Lewis 8x6 Supersonic Wind Tunnel. The tunnel drive consists of three mechanically-coupled 29,000 HP wound rotor induction motors driving an axial flow compressor. Liquid rheostats are used to vary the impedance of the rotor circuits, thus varying the speed of the drive system. The new design utilizes a distributed digital control system with a dual touch screen CRT operator console to provide alarm monitoring, logging, and trending. The liquid rheostats are driven by brush-type servomotor systems with magnetostrictive linear displacement transducers used for position feedback. The new system achieved all goals for speed variations with load, motor load balance, and control of total power.

## **INTRODUCTION**

The 8x6 Ft Supersonic Wind Tunnel/9x15 Ft Low Speed Wind Tunnel complex offers a unique combination of wind tunnel conditions for both high speed and low speed testing. For high speed testing the 8x6 SWT test section produces airflows ranging from Mach .36 to Mach 2.0 to accommodate both aerodynamic testing of inlets and nozzles or propulsion testing using burning jet and rocket engines. Capabilities for research testing at subsonic and near-ground regimes is offered by the 9-ft high, 15-ft wide test area in the return leg of the facility. Air speed in the 9x15 LSWT test section can range from 0 to 175 mph, and is varied using a combination of compressor speed and the position of the tunnel flow-control doors. The 9x15 LSWT facility design allows high angle of attack testing up to 180°.

The testing requirements for the two wind tunnels make severe demands on the drive control

system. For subsonic testing, maintaining a selected compressor speed over a range of 500 to 875 rpm is essential because it directly effects the test section velocity. For supersonic conditions, a change in the compressor speed changes the 8x6 test section temperature, which can cause a drift in a model force balance. The selected speed must be maintained over a drive power range from 30 to 72 MW during slow load changes caused by movement of the upstream throat (flexwall) and tunnel control doors, and with sudden load changes caused by operation of the downstream shock doors, model actuators, and model angle of attack. These requirements emphasize the need for a reliable, flexible, and accurate speed control system.

The three General Electric wound rotor induction motors are controlled by varying the resistance of the rotor circuit, as shown in Fig. 1. As the movable electrodes, called "sticks", are positioned at a greater distance from the fixed electrodes in the electrolyte tanks, the increase in resistance produces a proportional increase in rotor slip. This allows a variation in speed over a wide range below the synchronous speed of the motor.

The 8x6 SWT began operation in 1949 with a GE drive speed control system which employed an electro-mechanical programmer for function timing, and vacuum tube amplifiers and amplidynes (rotary motor-generator type power amplifiers) to drive the liquid rheostat pilot motors. In 1982, the system was replaced with a new GE design, which was similar to that used for an upgrade of the Ames Unitary Plan Tunnel speed control (see Ref. 6). This design used a combination of analog and digital circuitry for control and logic, but retained the original amplidynes to drive the rheostat motors. Two new features added with this system were a "Speed Seek" and a "Speed Hold".

This system had some very good capabilities. It controlled over a very wide range of compressor speeds and maintained constant rpm under varying loads. At low to medium loads it did a good job of sharing power between the three mechanically coupled motors, thus maximizing efficiency and preventing motor overload. However, there were also a number of problems with the system. It was difficult to troubleshoot problems and make repairs to the system because of the age and complexity of the circuitry and the poor availability of original parts. The hybrid nature of the system and the method of construction made it inflexible for modifications.

One of the key features of the system, the "Power Hold" function, never held the total drive power to the maximum level as it was designed to do. In addition, a serious problem frequently occurred when changing tunnel velocity from Mach 1.8 to Mach 2.0. At this highest drive power condition the rheostat sticks are very near the bottom of the tanks and the corresponding rotor currents are at their highest levels, nearing 3000 amps. At these conditions the old speed control system would often go unstable and the rotor currents would begin oscillating wildly, varying as much as 1000 amps on the analog panel meters. This unexplained phenomenon nearly always led to a "lockup" and loss of further speed control. At that point the only option was to bring the drive speed down manually, shut down, reset the system and start over. This mode of operation significantly impacted testing productivity whenever high power runs were necessary.

In 1989 the 8x6/9x15 facility underwent a major rehab which included a control room expansion, an air dryer upgrade, an improved data acquisition system, and a new distributed controls system. For the new controls, a Westinghouse Distributed Process Family (WDPF) system with touch-screen graphic CRT's was installed to provide high speed data logging, alarm monitoring, and automatic and manual operation of the systems used to set tunnel conditions, but not the tunnel drive motors. The system was designed to provide improved automation, high reliability and enhanced flexibility. The WDPF system has proved very successful in meeting these goals.

Another series of major facility modifications were planned for the 8x6/9x15 facility with construction activities from July, 1992 through March, 1993. This shutdown provided an opportunity to replace the existing drive speed control system with an updated design which would afford improved reliability and better capabilities. In September of 1991, a small team of engineers from the Lewis Aeropropulsion Facilities and Experiments Division was organized to plan the design, procurement and installation of a new drive control system.

### **NEW CONTROL SYSTEM COMPONENTS**

The decision was made to undertake this project as an in-house effort instead of through a contract for several reasons. A discrete project with Construction of Facilities (CoF) funding requires separate outside contracts for the preliminary engineering design, the final design, and the construction activities. This procedure would have been very costly and required a great deal of time. Since cost estimates were higher than planned for other parts of the facility modifications (installation of screens and honeycombs for flow improvements, replacement of drive power cables, etc.), it was imperative to reduce costs where possible to be within the budget for the CoF project. In addition, the operations engineers in the 8x6/9x15 facility had much experience and expertise in the facility equipment and systems, especially the WDPF distributed controls, which greatly aided the design of the necessary interfaces to the existing equipment.

The design team established several goals and strategies for improving the overall control of the wind tunnel compressor speed and drive motor operations. The overall system was analyzed down to the component level with the following areas of weakness identified and solutions proposed:

#### **Rheostat drive components**

1. The stick positioning pilot motor was a standard 1 HP shunt wound 125 VDC motor. Motors of this type do not have good torque output characteristics over their full speed range. In addition, even if used with a modern digital regenerative control unit and digital tachometer, the speed range is about 100:1. For optimum performance, high acceleration/deceleration torque and high torque at very low speed are needed.

**Solution** - A DC servo motor system was specified to replace the old DC shunt motors.

The system included a 1500 watt PWM servo drive and a completely sealed brush type servo motor with an integral tachometer. The system provided a continuous operating torque of 36 lb-in at 0 rpm and a maximum speed of 2700 rpm.

2. The gear reducing mechanism coupling the positioning motors to the stick positioning pulleys consisted of two separate gearboxes for a total speed reduction of 200:1. Besides unnecessary hysteresis caused by the backlash in the two gearboxes, the 200:1 speed reduction coupled with a motor with a maximum speed of 1750 rpm limited the response time of the stick positioning system.

**Solution** - A direct drive, two stage, right angle gearbox with a total speed reduction of 150:1 was chosen because it could directly accept the NEMA 56C flanged servo motor as well as be direct coupled (using a soft-start coupling) to the actual rheostat positioning pulley. The motor, gearbox and drive pulley system are all shown in Fig. 3. The speed reduction was decreased so that, when coupled to the new servo motor with its wide operating range, the overall speed at which the sticks could be positioned would be more than doubled, allowing for a much faster response time and minimum set point overshoot.

3. The old stick position feedback method used a one-turn wirewound potentiometer driven by one of the old gearbox output shafts, thus providing poor resolution and repeatability for the control system.

**Solution** - A magnetostrictive linear displacement transducer manufactured by Temposonics was selected to replace the old pancake style pot. Figure 3 shows how the new transducer is mounted in order to be free floating and independent of the stick drive system. Actual absolute stick position is obtained by reading the position of the counter balance weights over the completely linear 70" stroke. The selected device is repeatable to 0.001% (0.0007"), and is a key contributor to the overall effectiveness of the new speed control system.

### Monitoring, Instrumentation and Control Components

1. Prior to the upgrade, the drive monitoring equipment consisted primarily of analog panel meters located in the drive control room. Meters for currents, voltages and power displayed values for each of the three separate drive motors. A total power meter and chart recorder were used for historical data.

**Solution** - It was decided early on in the project to incorporate the new speed control system into the existing WDPF tunnel controls system to take advantage of the WDPF's monitoring, trending, and historical archiving capabilities as well as its excellent capability for analog control. New low cost off-the-shelf power, current and voltage transducers were purchased and installed as analog inputs into the existing WDPF. These inputs, together with the rheostat stick position feedback information, would form

the basis for the new speed control system.

2. The existing drive control panels were quite cluttered, with individual drive motor metering spread out over many feet of duplex panel space. This made it difficult for the operators to recognize problems building in the drive system, such as power imbalance.

**Solution** - Several new CRT control screens were created for the existing operators dual touch screen control console. A typical display graphic is shown in Fig. 2. The new control screens allowed the operators to view much more information on graphics displays that simulated the physical appearance of the drive system. The dual CRTs allow the operator to view more than one sub-system at a time. All of the critical inputs and outputs existing before and those added as part of the upgrade are monitored and alarmed on a facility alarm printer, as well as on the CRTs, and also on a hardwired annunciator system where appropriate. The duplex panels were stripped of several of their metering functions so that only critical drive information is now displayed.

3. The liquid rheostats contain an electrolyte solution which accounts for the limited conductivity between the two plates in the tank. One plate is fixed at the bottom of the tanks and the other is positioned by the new speed control system. As the per phase rotor current passes between the plates heat is created within the individual tanks. All nine tanks (three for each phase of the three motors) are tied to common headers and a common electrolyte system including a heat exchanger to cool the solution to a desired temperature. The solution's conductivity is inversely proportional to temperature so electrolyte temperature becomes critical at higher power drive motor runs. The old system was unreliable with valves that were too large and controllers that did not function properly.

**Solution** - Several new electrolyte control system components were added and valves sized properly to give adequate temperature control during high power running of the drive motors.

### Drive hardwired controls

1. The drive motor startup and shutdown controls were typical of what one might find in an old industrial facility using motors of this size. The control logic employed a large number of relays and mechanical timers to sequence the startup and shutdown of the three motors to prevent overload of the electrical power lines. The older relays were becoming increasingly more difficult and expensive to maintain. In addition, the drive had to be started from the duplex panels which were separated from the CRTs planned to be used for monitoring and control of the drive and compressor systems.

**Solution** - The hardwired drive controls were completely revamped with the goal of eliminating any relay logic used only for sequencing purposes. WDPF outputs and inputs were used in place of contacts and coils in certain circuits. Timing circuits and normal

start and stop sequencing functions were duplicated in software in the WDPF. Overall wiring and relay logic was reduced at least 30%. The circuits that were determined to be required for shutdown or other safety related functions remained as hardwired.

2. Several duplex panel controls were out of reach of the CRT console. Several were redundant given the addition of the CRT control station.

**Solution** - Key hardwired pushbuttons such as the "Emergency Stop" button were duplicated on the duplex panel adjacent to the new CRT control console. Extensive ladder logic was created to take the place of all the relay logic that had been eliminated. This also allowed additional safe guards to be installed in several control sequences where they were previously omitted or not considered because of the complexity in performing them using relay logic. The cluttered duplex panels were further cleaned up, patched and repainted for a new appearance.

## **CONTROL STRATEGY**

The new 8x6 drive speed control software in the WDPF uses a cascade controller approach, as shown in Fig. 4. Motor shaft rpm is used as a feedback signal to a speed controller, which outputs a common motor power setpoint to three individual power controllers. The setpoint for the speed controller is produced by a ramp generator which limits the rate at which a change in speed setpoint will be seen by the control. The local electric utility company will only allow a power rate of increase of 10 MW/min. and a decrease of 15 MW/min. This constraint is satisfied for both subsonic and supersonic operation with a constant ramp rate of 2 rpm/sec.

A software power clamp block replaces the "power hold" feature that never functioned properly with the old system. When employed, the power clamp feature allows the compressor speed to fall in order to maintain the total power setpoint if further load is placed on the drive motors (due to increased tunnel blockage, for example). This feature helps the drive motor operator from exceeding power agreements during peak utility load periods as well as preventing potential overload conditions on the drive system during the high power runs. When the power clamp is released, the control system immediately resumes using compressor speed as its primary control variable.

A diagram for one of the three rheostat positioning controls is shown on Fig. 5. The power controller uses motor power as a feedback signal. A variable gain and reset schedule, driven by stick position, is used to compensate for the non-linear relationship between rheostat position and motor power draw. The output of the power controller is a  $\pm 10$  volt velocity command signal to the servomotor controller.

For routine maintenance or repair, a manual mode may be used by the drive motor operators to position the rheostat sticks. This feature is disabled in the "online" mode.

In the event a system problem or failure is detected (such as a difference between the redundant



measurements of drive speed or power, a significant power unbalance between motors, a servomotor controller fault, or a rheostat overtravel) the sticks are frozen in their last position and a "normal shutdown" must be initiated. This policy is used because past experience has shown that it is impossible to instantaneously analyze what type of problem might be occurring during an "online" failure and that a incorrect action can cause further problems or failures to occur. If, for some reason, a "normal shutdown" cannot be used, the operator can push the "Emergency Stop" or "Fast Stop" button which will automatically bring the drive down from the loaded condition and set various tunnel controls to their safest positions.

Dynamic braking is used for all shutdown methods to bring the drive quickly to a complete stop after the last motor has been disconnected from power, unless a fault is detected that indicates this would cause harm to the drive system. The dynamic braking is enabled after a slight delay, during which motorized transfer switches physically switch the stator wiring of the first two drive motors into a series configuration with a DC MG set. DC current is pumped around this loop and bucks the rotating field of the still spinning rotor. The drive reaches zero speed in about two minutes, after which, the WDPF resets all systems and the drive is ready to start again. The rheostat sticks for Motors 1 and 2 are controlled to provide maximum motor deceleration during the dynamic braking operation, while the rheostat for Motor 3 is set to the upper limit. After shutdown, the servomotor drive outputs are disabled to prevent drift of the liquid rheostat electrodes.

## **CHECKOUT AND TUNING**

A detailed Integrated Systems Test (IST) plan was written for the component, subsystem, and system checkouts, and also for the operations and tuning procedures required for each tunnel run. The first checkout runs were performed under manual control to check the integrity of the newly installed flow improvement devices at subsonic conditions. Once these devices were cleared for all operating conditions, the power controllers for the drive were tuned. Since the power controllers use a variable gain and reset to compensate for the extreme nonlinearity of the rheostat, the tuning was done in a piecewise manner from the sticks at 50% to near the tank bottom. This procedure was followed by the tuning of the speed controllers and then the entire sequence was repeated for supersonic operation and for tunnel operation with exhaust of the test section boundary layer air. The new drive speed control performed so well that tuning could progress from the initial motor bump to full power runs in less that three days of testing.

## **CONCLUSIONS**

The new drive control system met or exceeded all of the planned design goals. The system maintains a constant speed under varying loads over the entire 500 to 875 rpm operating range. Significant load changes, such as hard starting the tunnel with the shock doors or increasing Mach number from 1.6 to 2.0 produces less than 1% variation in speed. The motors change from base speed to any test condition in one step automatically on command. The power spikes and surges previously seen on rpm changes were totally eliminated. The system provides the

sensitivity to hold the power imbalance between the three motors to less than 0.05 MW, which allows maximum output power to be delivered to the compressor. The violent power oscillations at high power levels have been completely eliminated, allowing speed increases even when the rheostats have less than 1 % travel remaining. Electrolyte temperature, which previously climbed during prolonged high power runs, can now be held within 1 °C of setpoint. This eliminated the speed drift caused by the conductivity change of the electrolyte with temperature.

The power hold feature, which automatically reduces drive speed to clamp total power to the value set, functions perfectly. The operator previously decreased speed manually in 5 rpm increments near Mach 2 to keep power from exceeding the 70 MW limit. This has reduced the time from the first motor start to Mach 2 from 26 minutes with the old system to 17 minutes now.

The installed cost of the new drive controls system was approximately \$165,000, compared with about \$600,000 for the upgrade installed by GE in 1983. Only 20% of the planned tunnel runs for checkout and tuning were required, which saved about \$175,000 in electrical power and manpower costs. The reliability of the new equipment has been excellent, with 100% readiness for scheduled runs to date.

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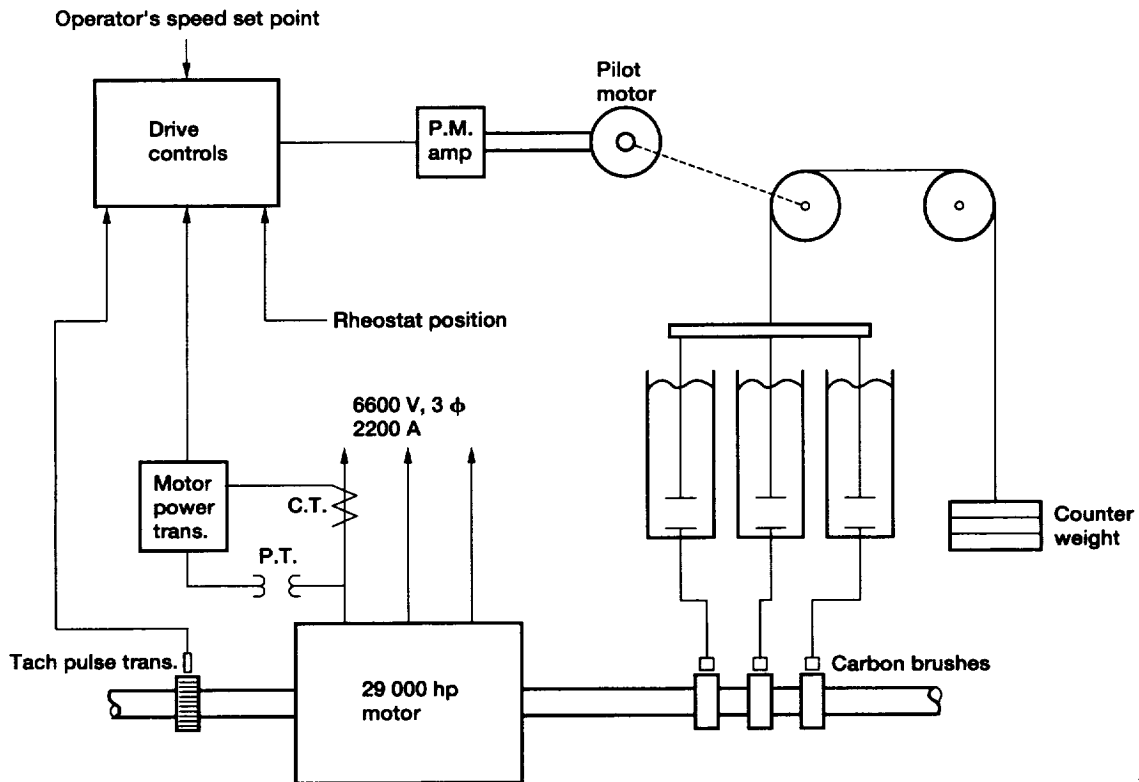


Figure 1.—Drive motor speed control schematic.

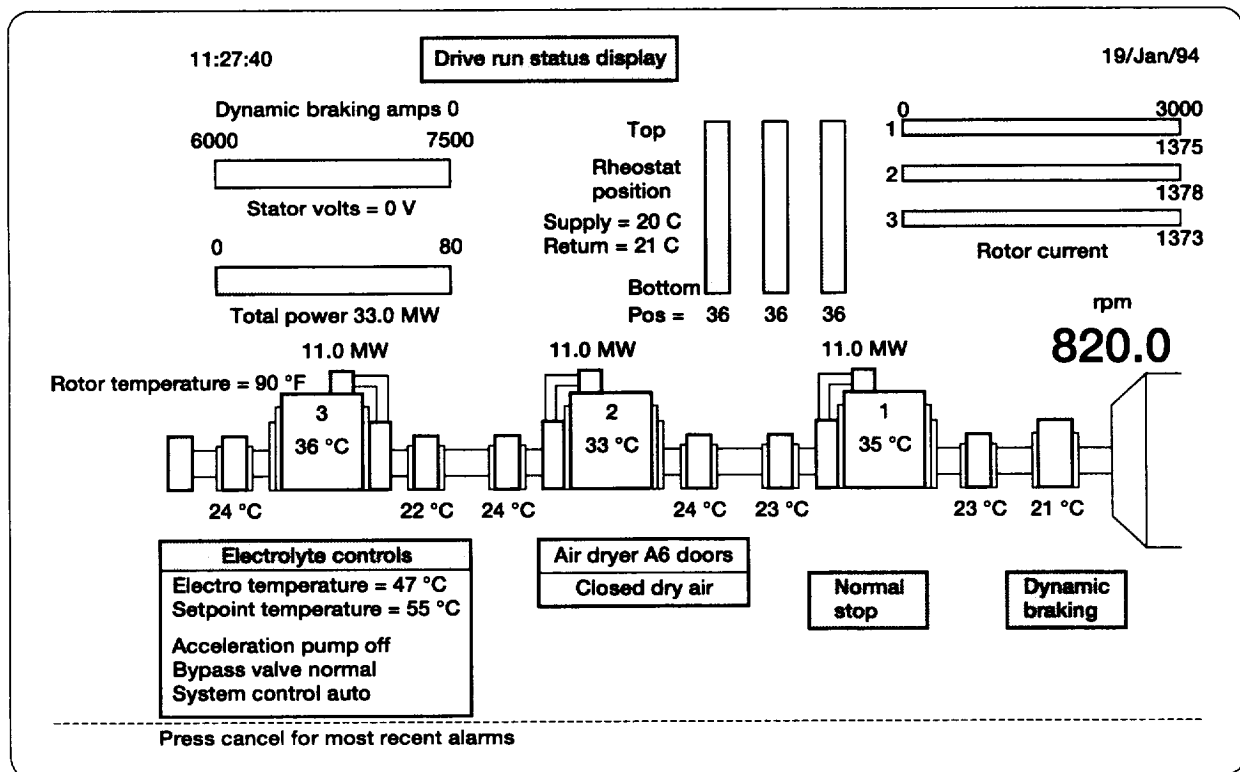


Figure 2.—Typical graphic control screen.

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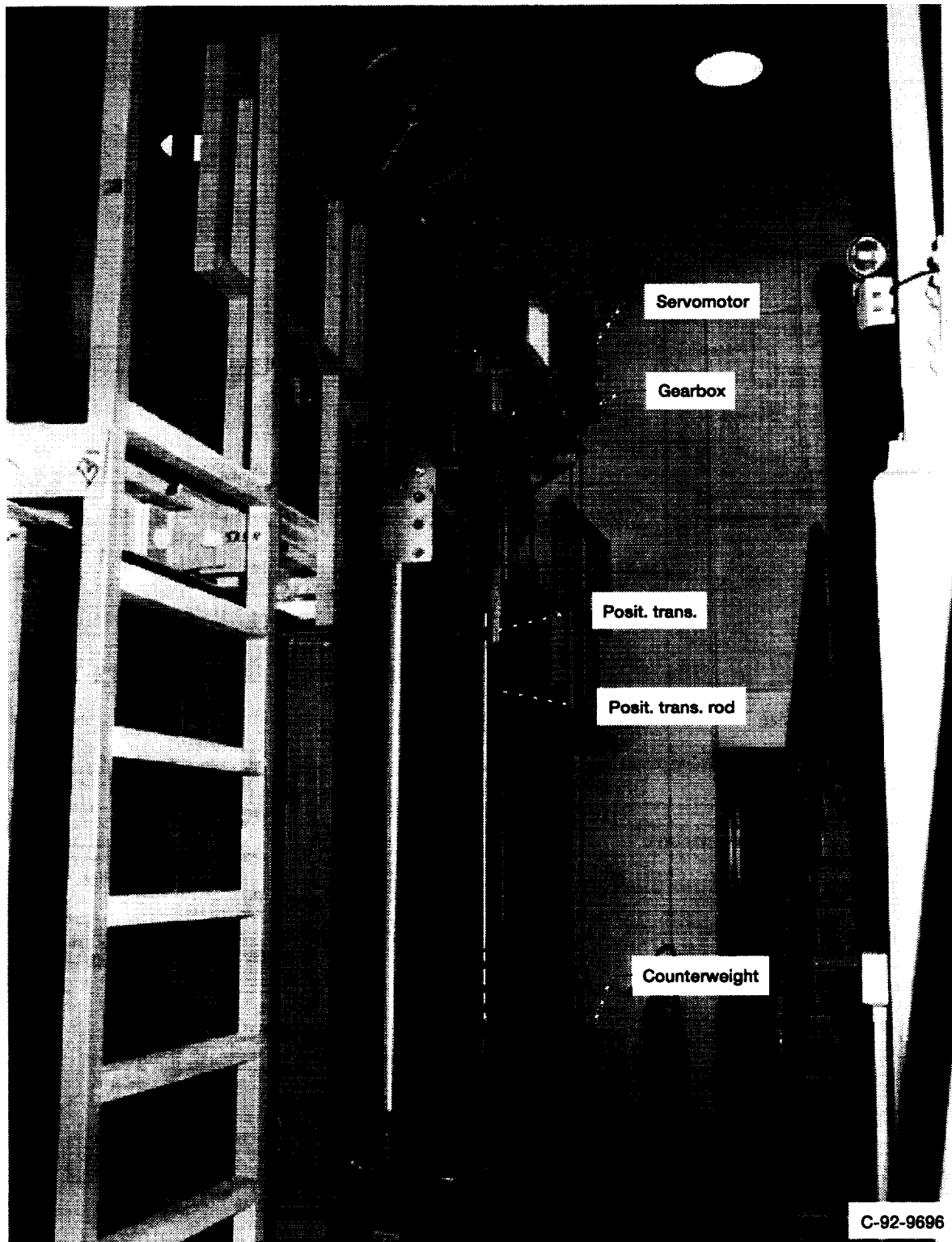


Figure 3.—Liquid rheostat control.

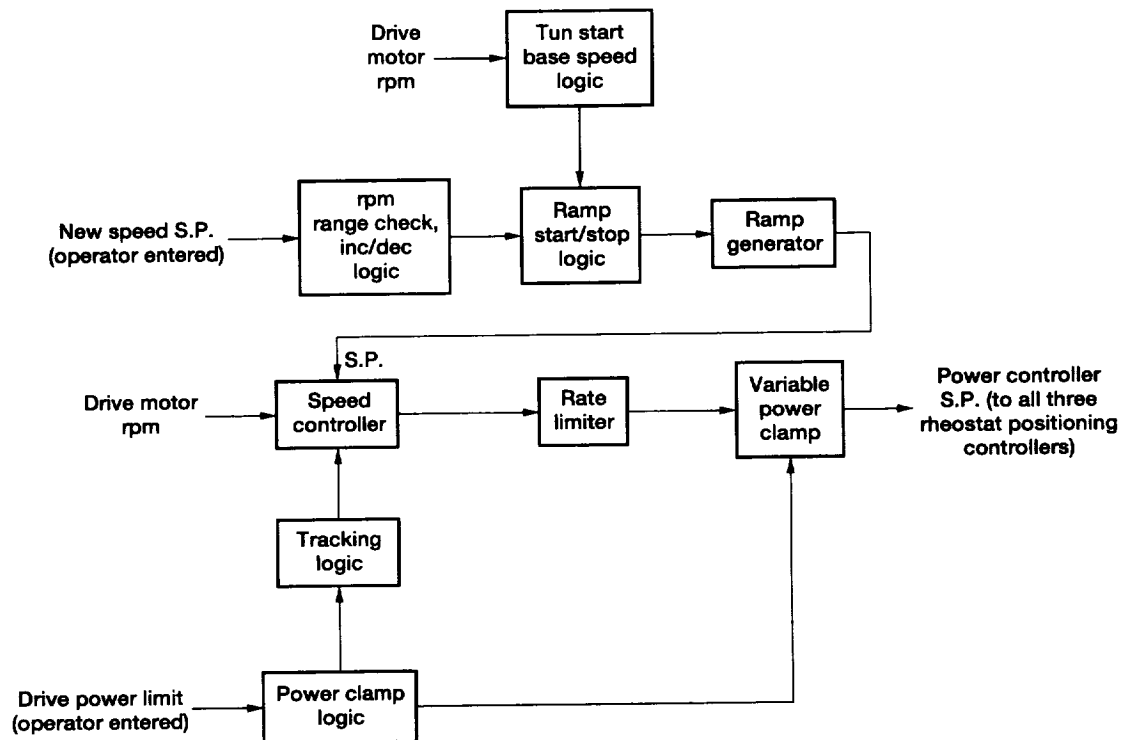


Figure 4.—Rpm/power set point generation.

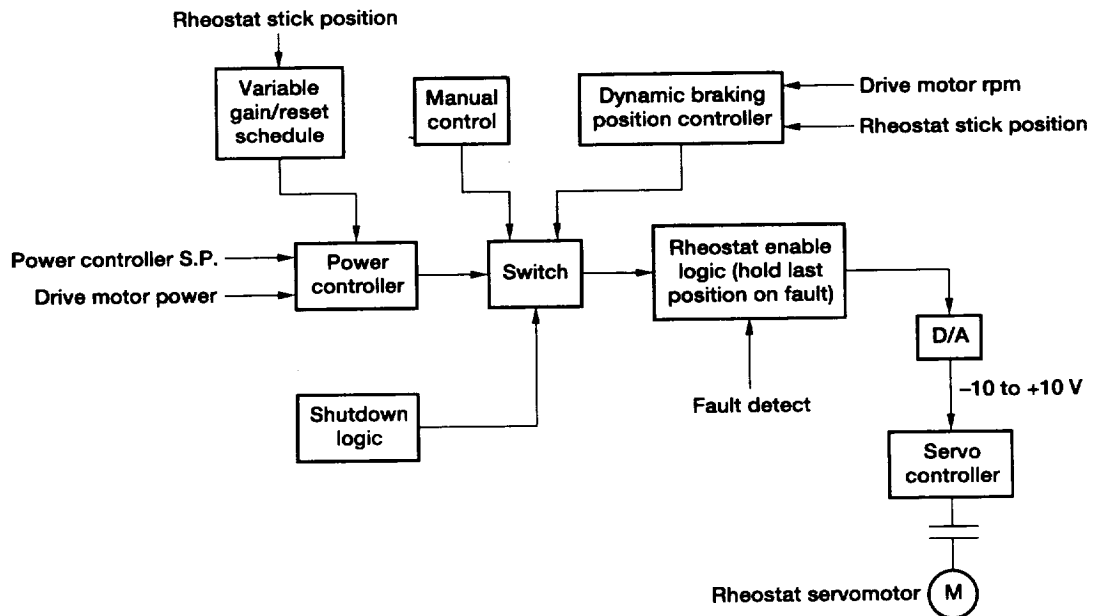


Figure 5.—Rheostat positioning control.

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